Neutrinos and Implications for Physics Beyond the Standard Model

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Neutrinos, Past and Present[1]

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It is a happy coincidence that this conference starts a few days after the Nobel Prize was awarded to Ray Davis and Toshi Koshiba for their pioneer work on extra-terrestrial neutrinos.

Ray may be amused to be reminded of something I learned from Blair Munhofen, who worked with Ray: He happened to overhear a conversation between my late wife Trude and Ray who said that he was worried that he did not detect enough neutrinos. She remarked "that may be more interesting."

Toshi may be glad to hear that at the 1998 Neutrino Conference in Venice, I showed transparencies indicating - because the neutrino temperature in a supernova collapse first rises, then falls - that Kamiokande, which could detect lower energy neutrinos than IMB, observed neutrinos ~1.5 sec earlier than IMB!

Robert Shrock originally asked me to concentrate on my earlier work, especially on neutrino helicity and on the beginning of the search for proton decay. But it dawned on me that this sounds more like an after-dinner talk than an after-breakfast talk, and Robert kindly allowed me to change the title of my talk. I shall still mention some older work and discuss in detail some recent work.

In discovering radioactivity in 1896, Henri Bequerel detected the first weak interaction, the β-rays from a uranium daughter product. After the discovery of the electron and evidence

[1] This work was performed under the auspices of USDOE under Contract No. DE-AC02-98CH10886

that β-rays also have negative charge, he considered them to be electrons, though half a century later some physicists still searched for a possible small mass difference between β-rays and electrons by measuring e/m for each with increasing precision.

In 1948 my wife and I realized that precision experiments in which each kind of particle is *separately* measured could not reduce errors sufficiently to prove a zero difference. We were confronted with a dichotomy, an either-or question: Are the atomic electrons identical with β-rays or not? We decided to try to settle this dichotomy by a simple decisive tabletop experiment that should answer yes or no. By stopping β-rays in Pb, they would, if *not* identical with electrons, fall into the K-Shell emitting slightly modified 'characteristic' x-rays and, if identical, Pauli's exclusion principle would say: Sorry, full up! We found no x-rays (1), and this ended the debate.

In 1957 contradictory experiments on the nature of the β-interaction were published, one showing that the β-interaction was Tensor, and, by implication, also Scalar (2) while the other concluded that the interaction was Vector, and, by implication, also Axial (3).

Again, this was an either-or question that we answered by a yes or no experiment (4). Neutrinos emitted in K-electron capture would have either right-handed helicity if the interaction were T and S or left-handed helicity if the interaction were V and A. We found left-handed helicity, thus deciding for V and A. We called our experiment "Helicity of Neutrinos". At that time neutrinos were believed to have zero mass, for which helicity and chirality are equal. An operationally more cautious title would have been: "Helicity of Neutrinos Emitted in K-electron Capture", that would have left open the question whether neutrinos are intrinsically left-handed or whether the weak interaction produces left-handed neutrinos, as we now believe.

While I was visiting Los Alamos in the summer of 1954, I realized that the absolute stability of the proton, then assumed as *obvious* by several distinguished theorists (Weyl, Stueckelberg and Wigner) should be tested experimentally. If protons were not stable, but could decay, conserving energy, thus releasing particles of nearly 1GeV total energy, one should be able to detect the decay, e.g., in a large scintillation counter, of the type then used by Reines and Cowan to study atmospheric neutrinos. I went to see them, and they were easily persuaded to do so. So while the start of the search for proton decay (5) was parasitic to a neutrino experiment, this situation later was reversed when larger and larger water Cherenkow detectors were built to search for proton-decay and neutrinos initially were considered a nuisance background. Over time, the neutrino research became important in its own right and the experiments became symbiotic, rather than parasitic.

Let me now talk of some recent work.

Approximate Evaluation of the Neutrino Mass Eigenstates. The Super-Kamiokande collaboration (6) established the existence of oscillations for atmospheric μ-neutrinos, and recently the SNO collaboration (7) obtained direct evidence for oscillations of the solar e-neutrinos, in agreement with the earlier indirect evidence of J. Bahcall, R. Davis and coworkers.

Oscillations prove that neutrinos have finite masses and that their flavor is not conserved. Finite neutrino masses are still often called a mystery because the SM predicts zero masses. In a recent paper (8) I offered several empirical rules for elementary fermions. One rule states the following: Within each generation the mass of an elementary fermion is found to be correlated with the strength of *its* dominant interaction, and thus with the hierarchical universal interactions. This rule suggests that neutrinos, with their weak dominant interaction, should have small masses.

It often has been pointed out that oscillation experiments, yielding values for Δm^2 between different neutrino mass eigenstates do not allow us to distinguish - without further assumptions - between three possible scenarios: hierarchical, anti-hierarchical, or nearly degenerate eigenstates.

Inspecting the masses of the elementary fermions with equal dominant interactions, called a family f_i (see fig. 1), shows that the masses of the three generations are in hierarchical order, for $m_{f_i} < m_{f_{i+1}}$. Looking in more detail at Figure 1 one finds that the following sub–rule holds in each case:

$$m_{f_i}^2 \ll m_{f_{i+1}}^2.$$

Assuming that these rules also hold for the neutrino mass eigenstates the following relations follow:

$$m_1 < m_2 < m_3$$

$$\text{and} \quad m_1^2 \ll m_2^2 \ll m_3^2.$$

Since oscillations of atmospheric μ-neutrinos into e-neutrinos were not detected above the background of atmospheric e-neutrinos, two-flavor oscillations, $\nu_\mu \rightarrow \nu_\tau$, are considered to be a good approximation. From the measured survival probability

$p(\nu_\mu \rightarrow \nu_\mu) = 1 - \sin^2 2\theta \sin^2 (1.27\Delta_{32}m^2[\mathrm{eV}^2]\mathrm{L}[\mathrm{km}]/\mathrm{E}_\nu[\mathrm{GeV}])$ one obtains (6)

$$\Delta_{32}\,(m^2) \equiv m_3^2 - m_2^2 \approx 2.5 \times 10^{-3}\,(\mathrm{eV})^2.$$

From the preferred LMA MSW solution for solar neutrino oscillations, one obtains (7)

$$\Delta_{21}\,(m^2) \equiv m_2^2 - m_1^2 \approx 5 \times 10^{-5}\,(\mathrm{eV})^2.$$

Neglecting m_i^2 relative to m_{i+1}^2, we find

$$m_3 \approx \sqrt{\Delta_{32}} \approx 5 \times 10^{-2}\,\mathrm{eV}$$

$$\text{and } m_2 \approx \sqrt{\Delta_{21}} \approx 7 \times 10^{-3}\,\mathrm{eV}.$$

The most accurately known f_i masses are those of the charged leptons. It is of interest to compare the ratios m_i/m_{i+1} with the ratios $m_{e_i}/m_{e_{i+1}}$ that are intermediate between the ratios for the u_i and d_i families. We find that $m_2/m_3 \approx 1.4 \times 10^{-1}$, which is ~2.4 times larger than the ratio

$$m_\mu/m_\tau = \frac{105.66}{1.777 \times 10^3} = 5.9 \times 10^{-2}.$$

Assuming, as an approximate guide, that the masses of the ν_i and e_i families are nearly parallel on a log scale, one obtains

$$m_1/m_2 \approx m_e/m_\mu = 4.8 \times 10^{-3}.$$

To estimate the uncertainty of the m_1 value I assume for m_1/m_2 a similar deviation by the factor ~2.4, as found for m_2/m_3. However, in this case, it may be safer to assume that the deviation could be in either direction, yielding a range for

$$m_1 \approx (1\text{-}5) \times 10^{-5}\,\text{eV}.$$

As a further test we deduce m_1 differently by using the relation

$m_1 = m_e/m_\tau \cdot m_3 = \dfrac{0.51}{1.777 \times 10^3}\; 5 \times 10^{-2}\,\text{eV} = 1.4 \times 10^{-5}\,\text{eV}$, which falls within the suggested range.

The KamLAND Collaboration (9) obtained a result compatible with the LMA MSW solution, preferred by SNO. Such a solution would independently suggest $m_2 > m_1$ implying a hierarchical order of the neutrino mass eigenstates involved. In Figure 2, the estimated neutrino mass eigenstates are compared with the masses of the other elementary fermions, given in Figure 1, and are shown in Figure 3 on a linear energy scale. The masses obtained for the neutrino mass eigenstates are $10^{11\pm1}$ times smaller than those of the corresponding charged leptons.

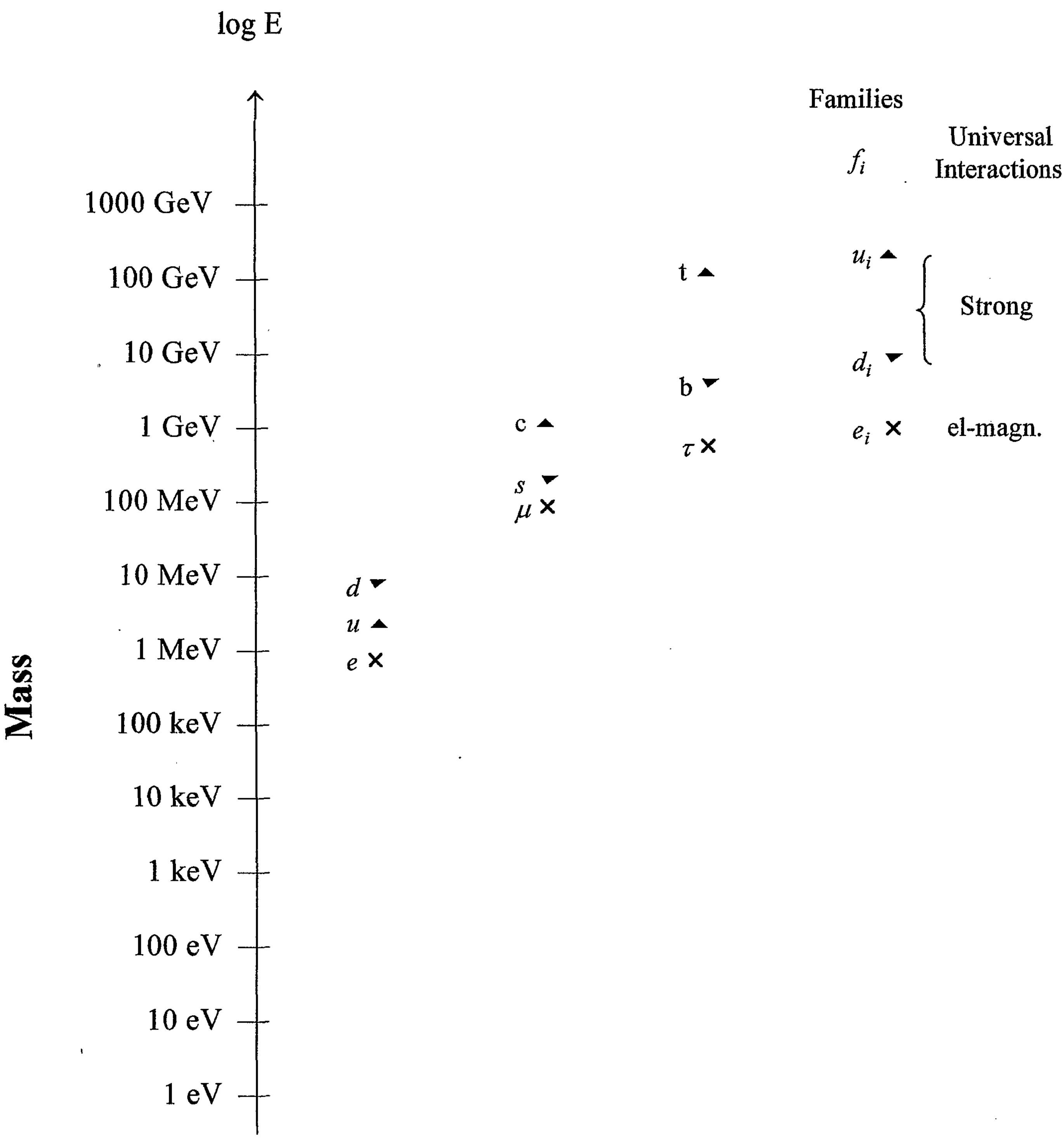

Figure 1

The mean of the masses of the elementary fermions.

For quarks the so-called 'current' masses are given, obtained from lattice calculations at ~2 GeV, except for the directly measured mass of the top quark (3). The *u* and *d* masses are deduced from their calculated difference (5) and ratio (6).

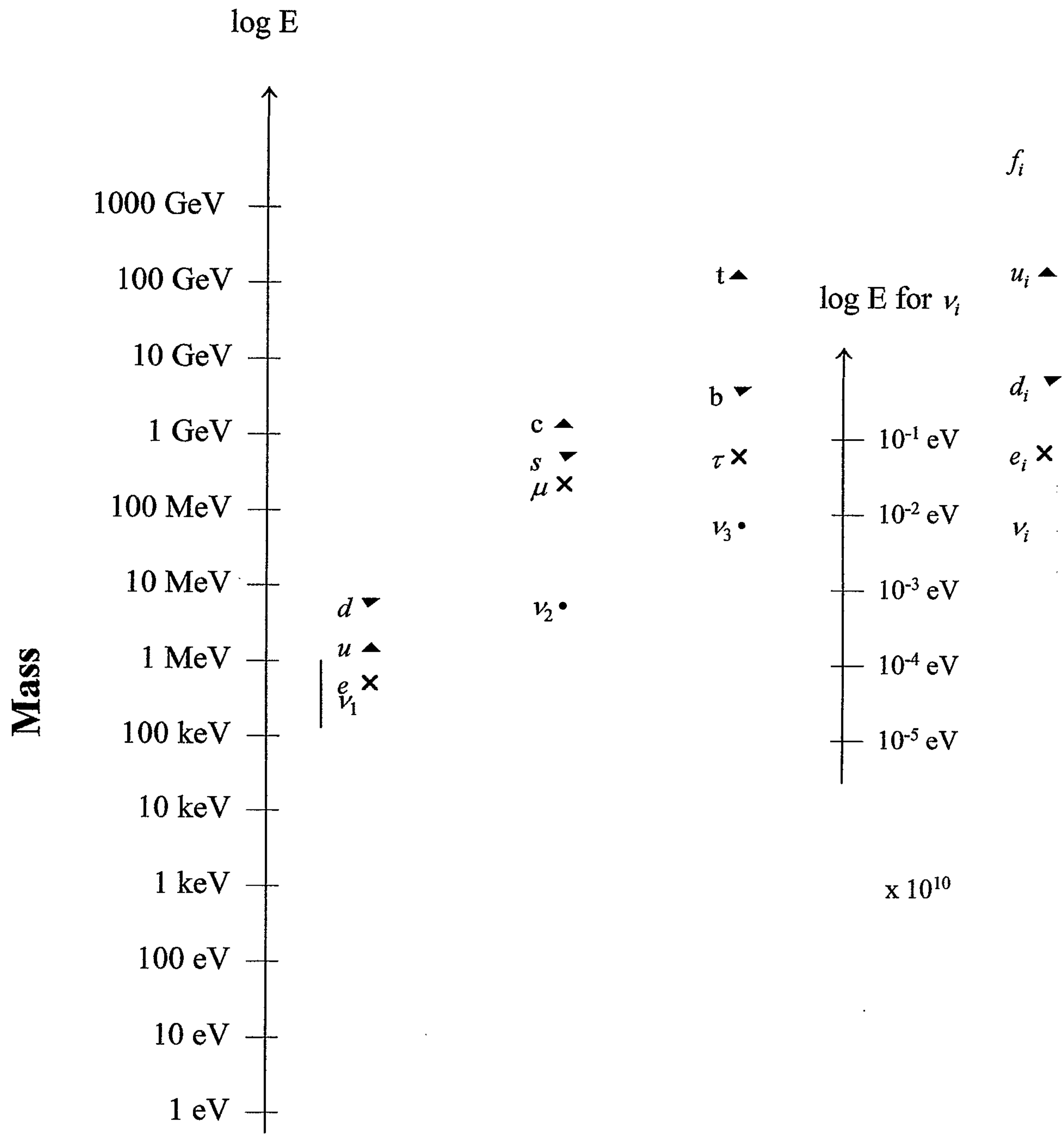

Figure 2

The mean masses of the elementary fermions (left scale) and of the approximate neutrino mass eigenstates - moved up by a factor of 10^{10} (right scale). The line to the left of the symbol ν_1 indicates the uncertainty in its proposed mass.

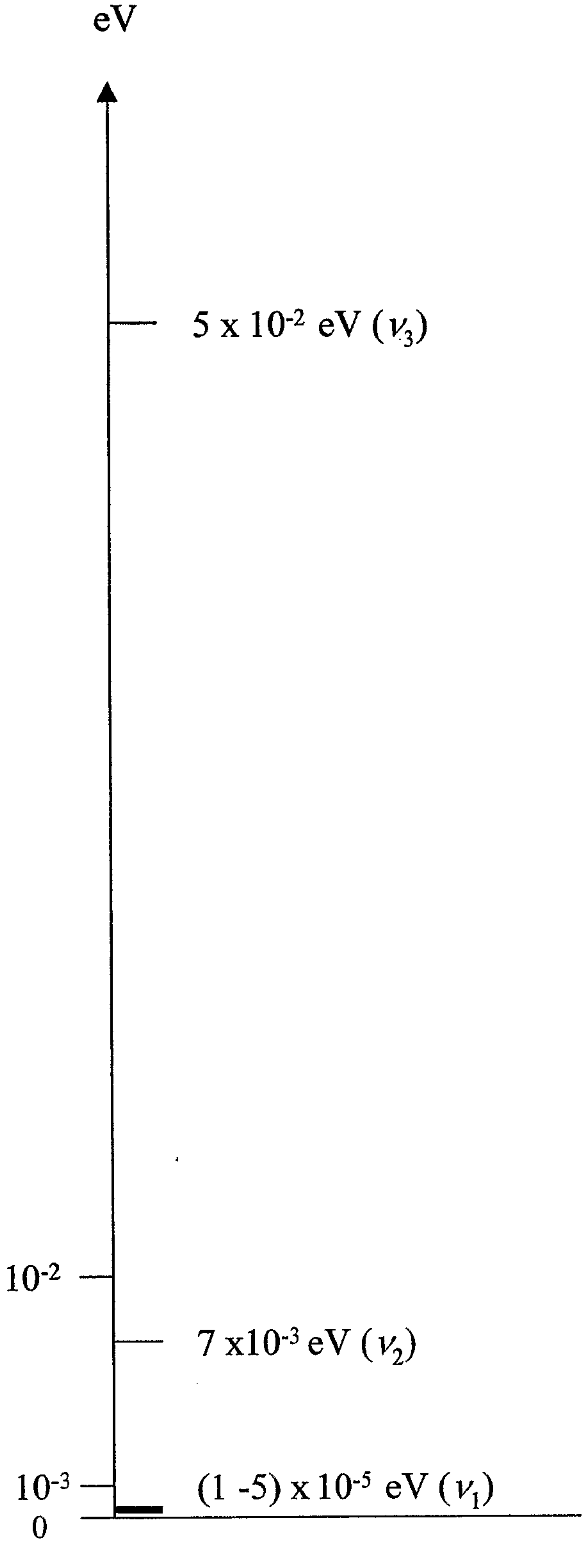

Figure 3

The estimated values of the neutrino mass eigenstates.
The thickness of the line for ν_1 symbolizes the estimated uncertainty in its mass value.

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